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ENDOSCOPIC MEASUREMENTS USING A PANORAMIC ANNULAR LENS

Submitted to

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center
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TABLE OF CONTENTS

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1. Research Objective

The objective of this project was to design, build, demonstrate and deliver a prototype system for making measurements within cavities. The system was to utilize structured lighting as the means for making measurements and was to rely on a stationary probe, equipped with a unique panoramic annular lens, to capture a cylindrical view of the illuminated cavity. Panoramic images, acquired with a digitizing camera and stored in a desk top computer, were to be linearized and analyzed by mouse-driven interactive software.

2. Tasks Scheduled During the Performance Period

The tasks to be completed were to a) characterize the panoramic imaging system, b) develop a probe for measurement within cavities, c) develop techniques for data acquisition, image processing and computer analysis, and d) deliver a breadboard system for cavity inspection and/or measurement.

3. Work Accomplished During the Performance Period

a) Characterization of the panoramic imaging system:

A panoramic imaging system was characterized by doing ray tracing on a panoramic annular lens (PAL), running a lens design program to determine suitable characteristics for a matching transfer lens and assembling the PAL/transfer lens combination shown in Figure 1. The system includes a 38 mm-diameter PAL and an f/1.4, 25 mm focal length transfer lens. The field of view extends from approximately -20 degrees below the lens to approximately 25 degrees above the lens. Optics were packaged with a "C" mount so that the system could be attached to a standard video camera.

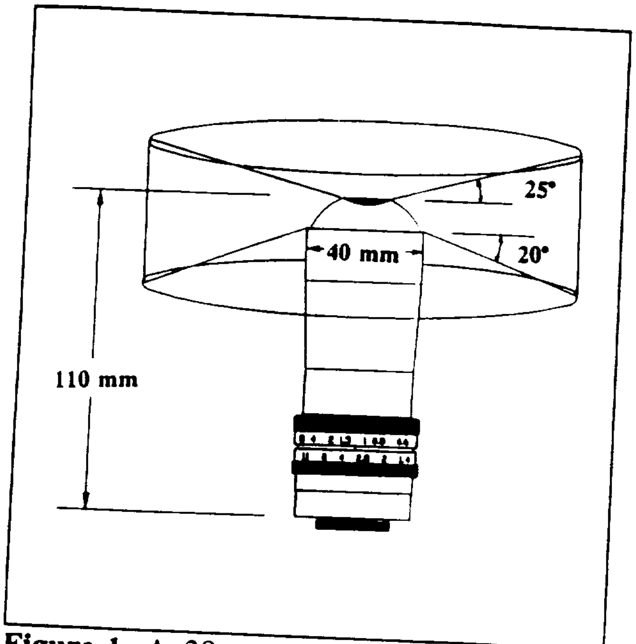

Figure 1. A 38 mm diameter PAL imaging system manufactured by Optechnology, Inc.

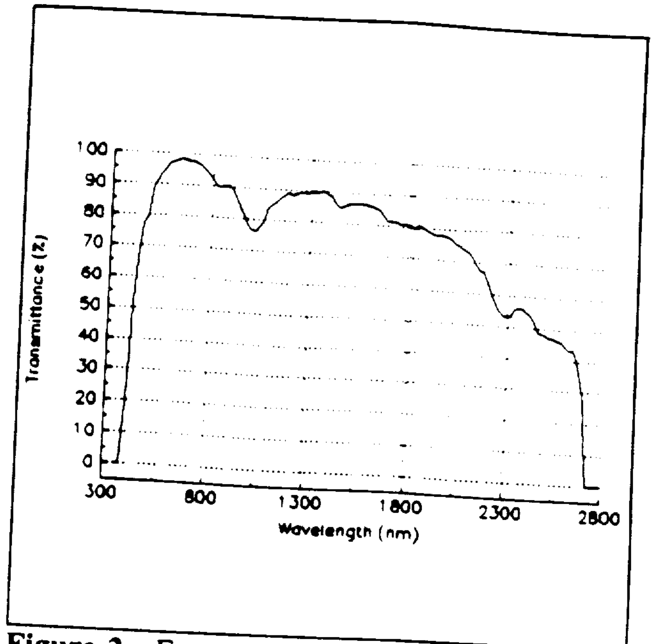

Figure 2. Frequency (wavelength) response curve for the PAL system shown in Figure 1.

The 38 mm-diameter PAL was characterized in terms of spherical aberration and coma, distortion, image plane curvature, and the modulation transfer function. The spherical aberration present in the PAL is comparable to a normal lens' spherical aberration in terms of the shape and size of the caustics, ranging from extremely small caustics to relatively large caustics. The marginal longitudinal spherical aberration and the marginal spherical aberration for a mid-field of view point are 0.05 inches and -0.03 inches, respectively. These values increase as the field angle varies from +25 to -20 degrees.

In general, the acceptance angle of the PAL also varies with field angle and the amount of spherical aberration is proportional to the acceptance angle. Moreover, the magnification varies quadradically and image plane curvature is cubic. Since the position of the image plane is slightly different for different object distances, the PAL is not strictly afocal. The frequency response of the PAL, normalized to 100 percent at 750 nm is shown in Figure 2.

The modulation transfer function (MTF) was found for both radial image lines and concentric image circles. The MTFs for the radial image lines indicate that the PAL has an azimuthal angular resolution of 0.0029 radians for the mid-field of view if the limiting MTF for the detector is equal to 0.05. The MTFs for the concentric image rings indicate that the PAL has a polar angular resolution of 0.0047 radians for the mid-field of view if the same limiting MTF is used.

b) Prototype system for optical inspection and measurement:

Problems of illumination, image acquisition, data storage and image analysis had to be addressed before a prototype system could be designed and built for optical inspection and measurement.

Prior contractual research showed that the illumination for inspection could be produced by surrounding the PAL system with a number of incandescent bulbs mounted and wired onto an aluminum ring. Problems with this illumination technique arose when using a protective cap to encapsulate the ring and the panoramic imaging system. Glare from the bulbs due to reflections off the cap was pronounced in the panoramic image and a uniform illumination of the cavity interior could not be achieved. Fear of excess heat generation from the incandescent bulbs was also a factor in exploring alternative means of illumination.

Several other approaches for illumination were considered including the use of holographic optical elements and a second panoramic annular lens. However, the diffraction efficiencies of the holographic elements were too low to produce the desired intensity while the costs associated with a second PAL were too high to justify the approach. A more plausible solution was discovered using waveguide technology.

A waveguide is simply a transparent material, such as glass or acrylic, with optically polished parallel sides. Light, directed into one end of the waveguide, propagates and is confined within the waveguide by total internal reflection. Upon reaching the opposite end of the waveguide, the light exits. However, if the waveguide is ground and polished to an angle, such that the incident angle of the light ray is greater than the critical angle as determined by Snell's Law, then the light will reflect completely off the angled portion and exit through the side of the guide. A cylindrical waveguide was designed based on these principles. Feasibility tests showed that the cylindrical waveguide could be used to successfully transmit light from a remote source to the cavity wall. An added advantage of the waveguide was that it could be used to protect the PAL system.

Diffraction gratings, waveguide techniques, a conical mirror system, and scanning methods were considered to produce the structured illumination required for optical measurement. A design was chosen which relied on a laser diode and a rotating mirror to project a ring of light onto a cavity wall. The position of the ring in the annular image was related to the perpendicular distance between the cavity wall and the optical axis of the imaging system.

c) Data acquisition, image processing and computer analysis:

Data Acquisition

The PAL prototype was mounted on a CCD camera having a resolution of 512 x 484 pixels. The hardware platform selected to acquire and store images was an 80486 microprocessor running on a standard AT bus under the MS-DOS operating system. Images were acquired by a standard commercial frame grabber and processor and stored in the computer.

The 486-class machine has a clock speed comparable to a main frame, yet it is designed to operate in the work area without the need for specially controlled operating environments, it is relatively inexpensive, mass storage is very cheap, parts are readily available world-wide, and the bus architecture allows for integration and intelligent control of user-supplied boards. Digital image storage permits signal-to-noise enhancement algorithms to be applied to eliminate, or at least greatly reduce, undesirable signal contaminants. The computer's archival capability facilitates further analyses by several individuals and by different software algorithms, without the need for repeating the inspection. Images and their salient features can be readily compared to data recorded in other inspections, automated data analysis is possible, and independent third party evaluations can be made without relying on the expertise or subjective evaluation of a single investigator.

Image Processing

Direct visual interpretation of a PAL image is sometimes confusing for the unskilled observer. With this in mind, an algorithm was developed to allow the annular shaped images to be linearized for viewing and measurement purposes. It must be recognized that there is no easy way to present a nonrectangular image in a rectangular format without distortion. This is essentially the same problem as making a flat map out of a round globe. However, the type of distortion introduced can be chosen and controlled by the choice of mapping scheme that is used (equal maximal dimensions, equal areas, etc.). The mapping used here maintains equal maximal dimensions by 'rolling' the annular image along its outer circumference and moving all the pixels between the contact point and the center of the image to a vertical line in the final rectangular image.

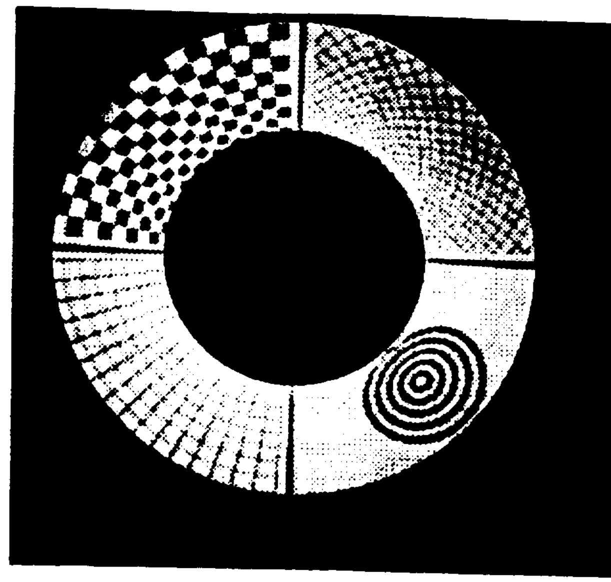

Figure 3. A test pattern as imaged by the PAL.

Figure 3 was used to test the linearization routines. The test drawing contains a different pattern, *i.e.*, diamonds, squares, checkerboard, and concentric circles, in each quadrant of the cavity wall. Referring to Figure 3, it can be seen that the distortion introduced by the FCP mapping is not severe, and the image is clearly recognizable. However, if it is desired to 'straighten out' the image, two stages of linearization are needed: (1) tangential linearization and (2) radial linearization. In the tangential linearization, a wedge-shaped portion of the annular image of the inside of the pipe is converted into a rectangular section. Next, because the annular image is not linear in the radial direction, a vertical stretching of the rectangular image is required; this second process is radial linearization.

The first step in linearizing the images obtained from the panoramic annular lens is to specify the size of the image. This is done by entering four (x,y) locations into the computer. The first three points are chosen on the outer circumference of the image. This allows the computer to calculate the outer radius and the center of the image. The last point is chosen anywhere along the inner circumference and allows the machine to determine the inner radius and the image height. An interface was designed to allow a user to select one of eight different quadrants (1-4, north, south, east, or west) of the image to be linearized. Once the points and the quadrant are chosen, the machine knows the entire segment that is desired and can proceed to straighten it out.

First the center location of the annulus is calculated, and then the height and width of the output rectangular image are determined in units of pixels. The final width of the image will be equal to the length in pixels of the outer circumference of the selected quadrant. Figure 4 illustrates how samples (shown as 'o's) in the annular image are mapped into a rectangular array. After the outer radial length is selected at one end of the specified quadrant, the radial angle is incremented until the other end of the specified region is reached; then the radius is decremented and the process is repeated. After this linearization, the number of columns in the image, which is determined by the angular increment used, is adjusted, by averaging, to have the same number as the outer arc length of the selected quadrant. Next the vertical height of the rectangle is then determined by calibrating the system. This calibration was accomplished for the 38 mm diameter PAL system by covering the interior cavity wall with a grid. Since the vertical and horizontal lines of the grid have the same spacing on the walls of the cavity, they should be equally spaced on the final linearized image. The spacing between vertical lines is taken as a reference and the spacing of horizontal lines in the rectangular image obtained after linearization is adjusted to obtain such a separation.

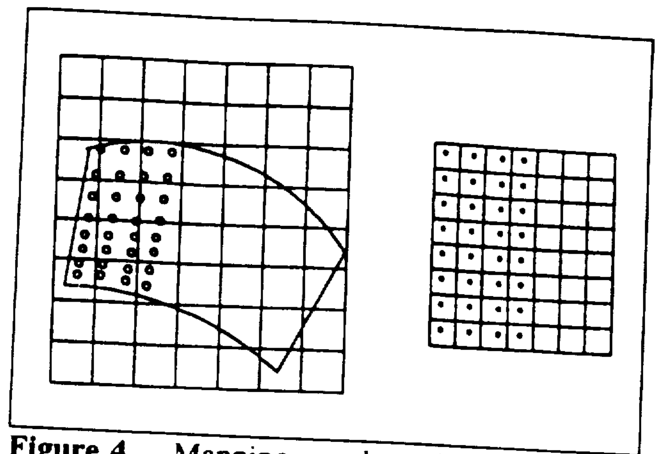

Figure 4. Mapping polar into cartesian coordinates.

Since a portion of the source image is being magnified by performing this linearization, a one-to-one mapping of source to destination pixels is not guaranteed. When an image is magnified, one pixel in the source image may be mapped to many pixels in the destination image. This source to destination pixel mapping is done from the perspective of the destination image. This reverse mapping is required to guarantee that every pixel in the destination image is given a value. Without the one-to-one correspondence between source and destination pixels it cannot be guaranteed that some source pixel will be mapped into each and every destination pixel. If there were no reverse mapping then there would be pixels that are not given a pixel value. These voids would degrade the appearance of the destination image.

Reverse mapping traverses the destination image space a pixel at a time and uses the transformation function to determine which pixel of the source image would be involved in producing the destination pixel.

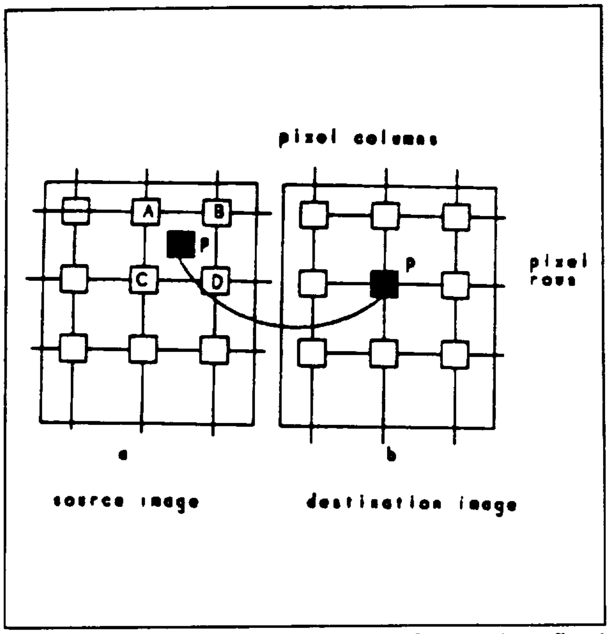

Figure 5. Reverse mapping from the final image to the source image.

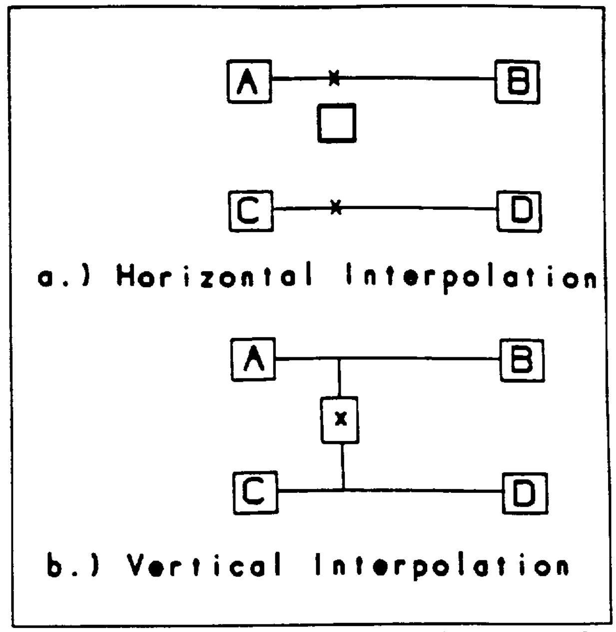

Figure 6. Interpolation of intensity values for non-integer coordinates.

However, reverse pixel mapping creates a second problem. There will be fractional pixel addresses. These occur when the source image pixel that contributes to a destination pixel's value is calculated. To deal with these fractional addresses an interpolation is performed to calculate a new value for some point with a non-integer (x,y) location that is situated between other points of known value. The corner points of known value that surround the point being calculated ('P', in our case) have a larger impact on the value of the calculated point than points further away. Assuming that the points are close together and that the intensity does not change rapidly with position allows the use of simple linear interpolation.

Figure 7. Linearized image of one quadrant of the test pattern.

In Figure 5, a pixel has a non-integer address. The intensity of the pixel [P] with non-integral address values of (x,y) is derived from the intensities of pixels [A], [B], [C], and [D] according to their relative distances from the calculated address of the transformed pixel. A two-dimensional interpolation is performed by making three linear interpolations of intensity values as shown in Figure 6. The grey scale values of [A] and [B] are interpolated first, and then the gray values of [C] and [D]. Using these two interpolated values as endpoints, the final result to be used as the grey scale value is interpolated linearly in the vertical direction. Figure 7 shows the final image obtained after applying both tangential and radial linearizations to the fourth quadrant of the image shown in Figure 3.

As mentioned previously, a measurement system was developed which relied on a laser diode and a rotating mirror to project a ring of light onto a cavity wall. A calibration procedure was developed to relate the radial offset distance (the perpendicular distance from the optical axis of the PAL to the surface under study) to the position of the point in the annular image. During this calibration, the laser light was projected on a surface that was progressively moved away from the optical axis of the imaging system. At incremental radial offset values, an image was acquired and the position of the scan measured relative to the center of the annular image was determined. The data was curve fitted and analyzed to obtain the sensitivity as a function of the radial offset distance.

Computer Analysis

A graphical user interface and mouse driven software package was designed and developed to facilitate image linearization and optical measurement. It is based on an extensive library of graphical tricks, developed and published by MIT, and includes buttons, scroll boxes, message boxes, and text keyins.

d) Delivery system:

A *Panoramic Video System* (PVS) was prepared as the deliverable under contract. The PVS relies on a PAL to capture a cylindrical view of the region surrounding the lens. Incandescent illumination is distributed over the cylindrical field of view using a light ring and waveguide. Measurement capabilities are provided by projecting structured light into the field of view. Panoramic images are acquired with a digitizing camera and stored in a modified image enhancer. The enhancer includes menu driven image processing software to linearize the annular images and make measurements within cavities.

The PVS includes:

1. A modified image enhancer running on a standard AT bus under the MS-DOS operating system. The enhancer consists of an 80486 microprocessor, 1 Mbyte of memory, a 40 Mbyte hard disk, two floppy disk drives (3 1/2" and 5 1/4"), a color VGA monitor and a serial mouse.

2. A panoramic imaging system consisting of a 38 mm diameter PAL with an f/1.4, 25 mm focal length transfer lens mounted on a standard video camera and a monochrome display monitor. The field of view extends from approximately -20 degrees below the PAL to approximately 25 degrees above the PAL.

3. A *Panoramic Video Interface* (PVI) for video input, control of illumination and measurement capabilities.

4. A CORTEX-I frame grabber and software package for transferring TIFF images, having a resolution of 512 x 484 pixels, from the camera to the image enhancer.

5. A 3" diameter *Data Acquisition Probe* (DAP) designed to house the panoramic imaging system. The DAP employs an optical waveguide for panoramic inspection and incorporates a laser diode for optical measurement.

6. An auxiliary 3" diameter *Cylindrical Light Ring* (CLR) designed to provide illumination when measurement and encapsulation are not required.

7. Two (2) 20' long composite cables for connecting the CLR and the DAP to the PVI.

8. PAL$^{\text{view}}$ software for panoramic image analysis.

The operator's manual which describes the PVI is appended to this report. A tutorial session was given to NASA personnel on September 28, 1992.

4. Potential Applications for Cavity Inspection and Measurement

Potential applications of the inspection system include detection of surface and near-surface cracks in weldments, detection of seams and foldovers in castings, monitoring of wear, and detection of structural failures. These applications are typically encountered in aerospace structures and propulsion systems where many components, designed to function at high temperatures and pressures, must be periodically inspected to avoid catastrophic failures.

For example, a visual inspection of the Main Combustion Chamber (MCC) throat of the Space Shuttle Main Engine (SSME) is required during manufacture, after each test firing, and as part of refurbishment between missions. The temperature is hottest in this region and periodic inspections are performed in an attempt to detect crack initiation, to monitor crack growth, and to observe surface roughness. Current inspection techniques require an inspector to insert their head into the throat and visually examine the nozzle contour. Cracks must be at least 3.0 inches or longer before they are recorded on a map of the MCC. The application of the PAL system should allow smaller cracks to be detected and, at the same time, eliminate the hazards associated with using support personnel to physically climb up into the nozzle. Moreover, the PAL system may eliminate the need for disassembling systems for inspection of their internal components; thereby, saving time and money.

An on-site tour of MSFC's SSME test stand generated significant interest in the project. Plans are currently underway to gain access to an SSME so that the main combustion chamber can be mapped using the PVS.

5. Personnel

The following graduate students received direct financial support:

Sara Fair (Ph.D. expected June, 1993 from UAH)
Wei Su (M.S. expected Dec., 1992 from UAH)
Joseph Puliparambil (Ph.D. expected Dec., 1992 from Marquette)

Other students at UAH and Marquette who contributed to the effort include Scott Caldwell, Sally Gronner, Christelle (Hendren) Lindner, Patrick Meyer, Michael Popp and Andrew Richter.

6. Publications and Presentations

Funding provided for this project helped support the following creative works:

Seminars:

1. Gilbert, J.A. "Panoramic inspection and measurement," Huntsville Electro-Optical Section and Working Group, Redstone Arsenel, Huntsville, Alabama, October 16, 1991.
2. Hendren, C.M., Gilbert, J.A., "Panoramic imaging systems for nondestructive evaluation," Alabama Space Grant Consortium Policy Advisory Committee Meeting, University of Alabama in Birmingham, Birmingham, Alabama, December 9, 1991.

Presentations:

1. Gilbert, J.A., Matthys, D.R., Lehner, D.L., Hendren, C.M., "Panoramic imaging systems for nondestructive evaluation," Proc. of the Third Conference on Nondestructive Evaluation for Aerospace Requirements, Huntsville, Alabama, June 4-6, 1991.
2. Gilbert, J.A., Matthys, D.R., Hendren, C.M., "Displacement analysis of the interior walls of a pipe using panoramic holo-interferometry," Proc. of SPIE's 1991 International Symposium on Optical & Optoelectronic Applied Science & Engineering, San Diego, California, July 21-26, 1991, pp. 128-134.
3. Gilbert, J.A., Matthys, D.R., Lehner, D.L., "Moire measurements using a panoramic annular lens," Proc. of SPIE's 1991 International Symposium on Optical & Optoelectronic Applied Science & Engineering, San Diego, California, July 21-26, 1991, pp. 202-209.
4. Matthys, D.R., Gilbert, J.A., Puliparambil, J., "Endoscopic inspection using a panoramic annular lens," Proc. of SPIE's 1991 International Symposium on Optical & Optoelectronic Applied Science & Engineering, San Diego, California, July 21-26, 1991, pp. 736-742.
5. Gilbert, J.A., Fair, S.B., "Panoramic endoscopy," Proc. of SPIE's Symposium on Optics, Electro-Optics, and Laser Applications in Science and Engineering, Los Angeles, CA, January 19-24, 1992.
6. Hendren, C.M., Gilbert, J.A., "Internal inspection of space hardware," Proc. of the

Southeastern Symposium on Experimental Mechanics, University of Alabama in Huntsville, Huntsville, Alabama, March 20-21, 1992, p. 8.

7. Meyer, P.E., Popp, M.A., Gilbert, J.A., "A graphical user interface for linearization of panoramic annular images," Proc. of the Southeastern Symposium on Experimental Mechanics, University of Alabama in Huntsville, Huntsville, Alabama, March 20-21, 1992, p. 22.
8. Beshears, R.D., Gilbert, J.A., "Non-destructive examination of rocket motor components," Proc. of the 1992 Conference on Advanced Earth-To-Orbit Propulsion Technology, Huntsville, AL, May 19-21, 1992.
9. Gilbert, J.A., Matthys, D.R., Hendren, C.M., "Panoramic inspection and measurement," Proc. of SPIE's Symposium on Image and Signal Processing, San Diego, CA, July 19-24, 1992.

Publication:

1. Matthys, D.R., Gilbert, J.A., Greguss, P., "Endoscopic measurement using radial metrology with digital correlation," Optical Engineering, 30(10): 1455-1460, 1991.

7. Conclusions

A new panoramic video system has been designed for visual inspection and measurement of aerospace components. It relies on a unique panoramic annular lens which produces a flat annular image of the entire 360 degree surround of its optical axis. The most outstanding attributes of the system are that the area surrounding the lens can be viewed simultaneously and the depth of field extends from the surface of the PAL to infinity. The annular image may also be linearized for improved human viewing. When a scanning system is incorporated, the panoramic video system can be used to make measurements within a cavity.

PAL systems are currently providing a new inspection capability for the SSME program and are expected to be applied for cavity inspection to verify the condition of space hardware after manufacturing, to perform inservice inspections following ground test engine firings, and to predict potential failure sites during refurbishment between shuttle flights. Current work to evaluate the potential for identifying and locating internal flaws, measuring the depth of surface cracks, comparing design contours to actual part contours, performing automated dimensional inspections, and imaging the relationship of the details in a complex assembly will be of tremendous importance to the space program.

8. Acknowledgements

The authors would like to acknowledge the interest and support of several personnel at the Marshall Space Flight Center including Jack Lee, Director; Bill Lucas, former Director; Ann Whitaker, Ken Woodis, and Ron Beshears of the Materials and Processes Laboratory; John

McCarty, Eric Hyde, Gary Lyles, and Jay Nichols of the Propulsion Laboratory; James Moses of the Research and Technology Office; and, Jonathan Campbell of the Space Sciences Laboratory.

APPENDIX

Operator's Manual

for the

The Panoramic Video System

Operator's Manual

for the

PANORAMIC VIDEO SYSTEM

Version 1.0

by

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Table Of Contents

Chapter 1

OVERVIEW

The *Panoramic Video System* (PVS) relies on a unique *Panoramic Annular Lens* (PAL) to capture a cylindrical view of the region surrounding the lens. Incandescent illumination is distributed over the cylindrical field of view using a light ring and waveguide. Measurement capabilities are provided by projecting structured light into the field of view. Panoramic images are acquired with a digitizing camera and stored in a modified image enhancer. The enhancer includes menu driven image processing software to linearize the annular images. Other software is included to aid in optical measurement and quantitative analysis.

The PVS includes:

1. A modified image enhancer running on a standard AT bus under the MS-DOS operating system. The enhancer consists of an 80486 microprocessor, 1 Mbyte of memory, a 40 Mbyte hard disk, two floppy disk drives (3 1/2" and 5 1/4"), a color VGA monitor and a serial mouse.

2. A panoramic imaging system consisting of a 38 mm diameter PAL with an f/1.4, 25 mm focal length transfer lens mounted on a standard video camera and a monochrome display monitor. The field of view extends from approximately -20 degrees below the PAL to approximately 25 degrees above the PAL.

3. A *Panoramic Video Interface* (PVI) for video input, control of illumination and measurement capabilities.

4. A CORTEX-I frame grabber and software package for transferring TIFF images, having a resolution of 512 x 484 pixels, from the camera to the image enhancer.

5. A 3" diameter *Data Acquisition Probe* (DAP) designed to house the panoramic imaging system. The DAP employs an optical waveguide for panoramic inspection and incorporates a laser diode for optical measurement.

6. An auxiliary 3" diameter *Cylindrical Light Ring* (CLR) designed to provide illumination when measurement and encapsulation are not required.

7. Two (2) 20' long composite cables for connecting the CLR and the DAP to the PVI.

8. PAL^{view} software for panoramic image analysis.

Chapter 2

USING THE PANORAMIC VIDEO INTERFACE (PVI)

The *Panoramic Video Interface* (PVI) is used in conjunction with either the *Cylindrical Light Ring* (CLR) or the *Data Acquisition Probe* (DAP). Two (2) 20' long composite cables are supplied for connecting the CLR and the DAP to the PVI. Each cable contains a video link with BNC plugs and a separate power cable. The power cable for the CLR employs a 4-pin connector at the PVI and a snap on connector and two quick disconnect plugs at the camera end. The power cable for the DAP employs an 8-pin connector at both ends; the end with the longer segment of video cable should be connected to the PVI.

Warning: The power to the PVI must be off before connecting the cables.

Connect the BNC and power cable to either the CLR or the DAP. Using the connectors located on the rear panel of the PVI, connect the BNC cable to the plug labeled input and use the 4-pin or 8-pin connector to connect the power cable. For obtaining live video during the initial setup, a cable with two BNC connectors may be connected from the plug labeled output directly to the display monitor. When image acquisition and processing are desired, the output of the PVI should be connected to the green RCA connector (Video In; see page 4 of the CORTEX-I manual) of the frame grabber packaged within the image enhancer. In this configuration, the display monitor must be connected to the red RCA connector (Video Out) of the frame grabber. Instructions for acquiring an image are included in Chapter 5.

Technical Note: A schematic of the front panel of the PVI is included in the Appendix as Figure A-3.

Warning: The control knobs located above the switches labeled measurement and illumination must be adjusted to their minimum positions before turning on the PVI. Failure to do so may result in permanent damage to the system.

Turn on the power to the PVI using the switch located in the lower right hand corner of the front panel. Turn on the video using the switch labeled video. The illumination light rings contained in the CLR and in the DAP are controlled using the switch labeled illumination; the intensity is adjusted by rotating the knob located directly above the switch. The measurement section is used to control a scanning mirror and a laser diode in the DAP. Turning on the switch labeled measurement starts the scan; the power to, and the intensity of, the diode is controlled by rotating the knob directly above the switch.

Warning: When the illumination system is no longer needed, the illumination knob should be returned to its minimum position and the corresponding power switch turned off. Operating the PVI over extended periods with the illumination control knob in its minimum position and the corresponding power switch on causes the temperature of an internal resistor to increase significantly. This condition may lead to reduced performance and/or component failure.

Warning: Extended use of the laser diode may also lead to reduced performance and/or component failure. When the measurement system is no longer needed, the diode should be turned off by returning the measurement knob to its minimum position. The measurement switch should be turned off to stop the scanning mirror.

Technical Note: The gain control, located at the back of the Pulnix TM-7CN camera, may be adjusted in conjunction with the illumination and measurement controls to further enhance the images obtained using the Panoramic Video System.

Chapter 3

DATA ACQUISITION PROBE (DAP)

The *Data Acquisition Probe* (DAP) is designed to encapsulate the panoramic imaging system. It employs an optical waveguide for panoramic inspection and incorporates a laser diode for optical measurement.

The DAP consists of 5 major components: the top cap; the main casing, which includes the scanning unit and window; the optics and camera assembly; the light ring; and the bottom cap. The components of the DAP are illustrated in Figure 3.1. The main casing, the light ring, and the bottom cap are attached through wiring that is threaded through each component. This wiring supplies the laser diode with power from the composite cable that is attached to the bottom cap. A description of the 5 major DAP components and their assembly follows.

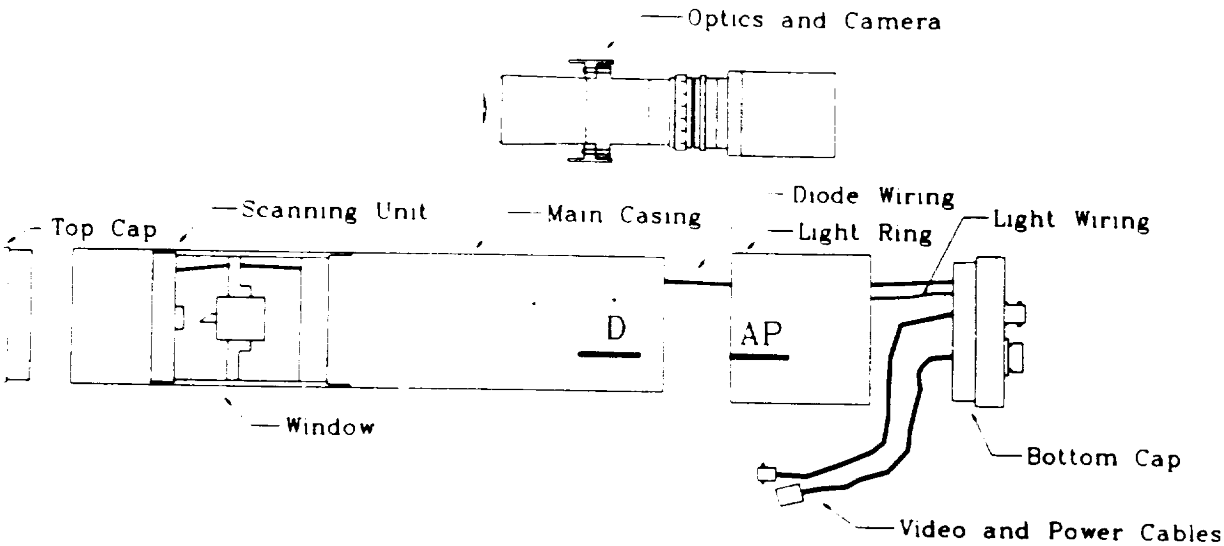


Figure 3.1 Components of the Digital Acquisition Probe (DAP).

Assembling The DAP For Panoramic Inspection

Optics and Camera Unit: The assembled optics and camera unit to be used within the DAP is shown in Figure 3.2. This unit is comprised of a 38 mm diameter PAL and its mount, 3 spacers, an f/1.4, 25 mm focal length transfer lens, and a Pulnix TM-7CN black and white camera. The first spacer has been designed to have an outer diameter that matches the inner diameter of the DAP, allowing the part to be firmly seated within the probe while minimizing a cantilever effect.

DAP Assembly: Refer to Figure 3.1 for illustration of each component during the assembly of the DAP. The assembled probe is depicted in Figure 3.3 and a hidden line view is illustrated in Figure 3.4.

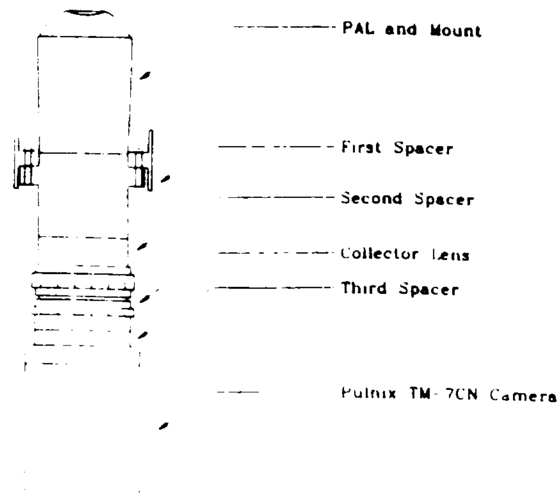


Figure 3.2 Optic and camera assembly for the DAP.

1. Thread the power and video cables attached to the bottom cap through the central hole in the light ring. Connect the corresponding power and video cables to the base of the camera.

2. The focus and aperture settings should be verified before inserting the optics and camera unit within the main casing of the DAP. Connect the composite power and video, 8-pin connector cable to the base of the DAP and the PVI. First turn the main power switch on, and then turn on the video switch as described in Chapter 2. With the aperture wide open, focus the collector lens on the PAL's virtual image while observing the adjustment on the video monitor. Note that the focus need not be adjusted after this initial setting. Next adjust the aperture to the desired setting. Note that an f-stop setting of 2 will allow inspection and scanning in most environments when the Gain control on the camera and the illumination and

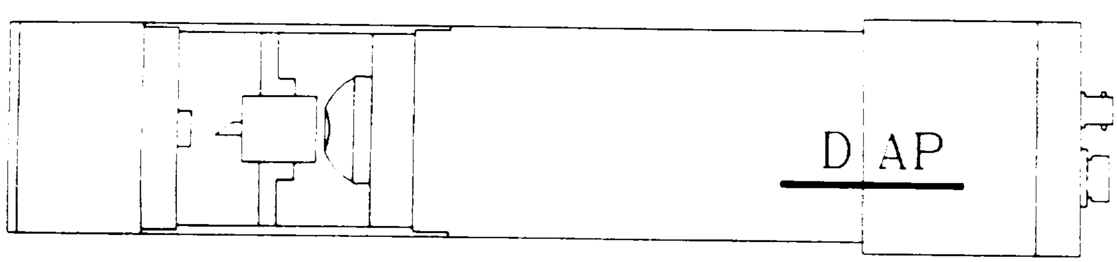


Figure 3.3 Assembled Data Acquisition Probe.

measurement intensity control on the PVI are used in conjunction with one another.

3. Position the alignment letters V, G, and P at the base of the light ring with respect to the position of the video, gain, and power labels on the camera base. With the alignment correct, carefully insert the camera within the light ring making sure the camera sits on the base of the light ring.

4. With the camera and light ring assembled together, align the DAP label on the outside of the main casing with the label on the light ring. Using minimal rotation, carefully slide the main casing into the light ring. Note that the countersunk holes on the light ring should be aligned with the threaded holes on the main casing.

5. Using a phillips head screw driver, screw the 1/4-28 countersunk screws into the 4 holes located at 90 degrees around the outside of the light ring. The remaining 4 holes may be used as ventilation. However, if complete encapsulation is required, using an allen wrench, carefully screw the (4) 1/4-28 set screws into the remaining holes. Screw these set screws until the outer surface is flush with the surface of the light ring.

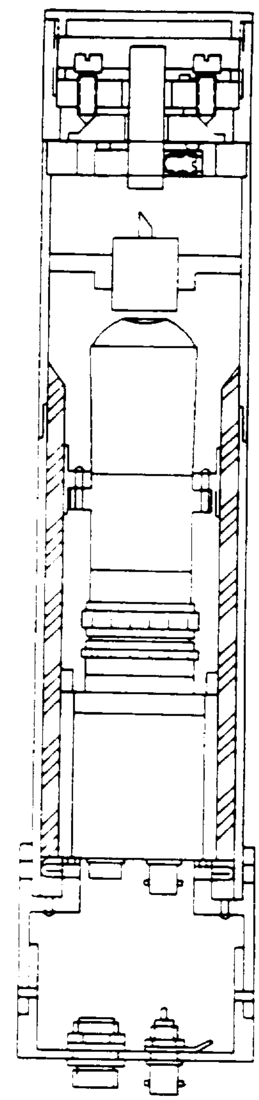


Figure 3.4 Data Acquisition Probe assembly drawing.

Warning: Screwing set screws too deep into the casing will result in damage to the bulbs contained in the light ring.

6. Wrap the video and power cables, along with the light and diode wiring attached between the main casing and the bottom cap, with the tie wraps provided. Place the wiring bundle within the light ring and then insert the bottom cap into the light ring.

7. Using an allen wrench, secure the bottom cap with the light ring using the (3) 6-32 set

screws provided.

8. Screw the top cap screw into the main casing at the scanning unit end to fully encapsulate the probe.

Replacing The Light Bulbs In The DAP

The DAP uses (8) T-1 3/4, 12 volts, .075 amp miniature lamps. The bulbs have been inserted from the inner diameter of the light ring and are positioned radially. A clearance of at least 1/8 inch has been secured between the outer wall of the light ring and the bulb tip to insure that the main casing will not crush the bulb when assembled. This clearance along with the ground is established with set screws on the top of the light ring. Four of the eight bulbs have been shortened in length to allow clearance on the inner diameter of the light ring for the video and power cables.

Instructions for bulb replacement follows:

1. The broken/burnt bulb must first be removed by removing the soldered connection to the wiring and by loosening the set screw in the light ring.

2. Insert the new bulb into its position and insure that at least 1/8 of an inch clearance exists between the end of the bulb and the wall of the light ring. Secure this position with the set screw.

   Technical Note: If the bulb to be replaced is one that has been shortened in length, the new bulb must also be shortened. Using a knife, carefully remove 1/8 of an inch from the end of the bulb. Fill the bulb with epoxy.

3. Solder the end of the bulb to the wiring. The connection can be verified by connecting the 8 pin composite cable to the bottom cap and then turning the main power and illumination power switches on as described in Chapter 2.

Aligning The DAP For Panoramic Measurement

Use of the measurement system requires alignment of the laser diode housed within the scanning unit of the main casing. The laser must be aligned with the shaft of the spinning mirror to insure that a complete and concentric ring is projected with respect to the optical axis of the PAL. This simple alignment procedure need only be performed once, however, periodic verification is suggested. Refer to Figure 3.5 during the alignment/verification procedure. Instructions are as follows:

1. With the probe assembled and cables connected properly, place the 10.5" (26.7 cm) diameter alignment disk on the probe with the concentric rings facing the scanning unit. The disk should be located at some point along the window as shown in the figure.

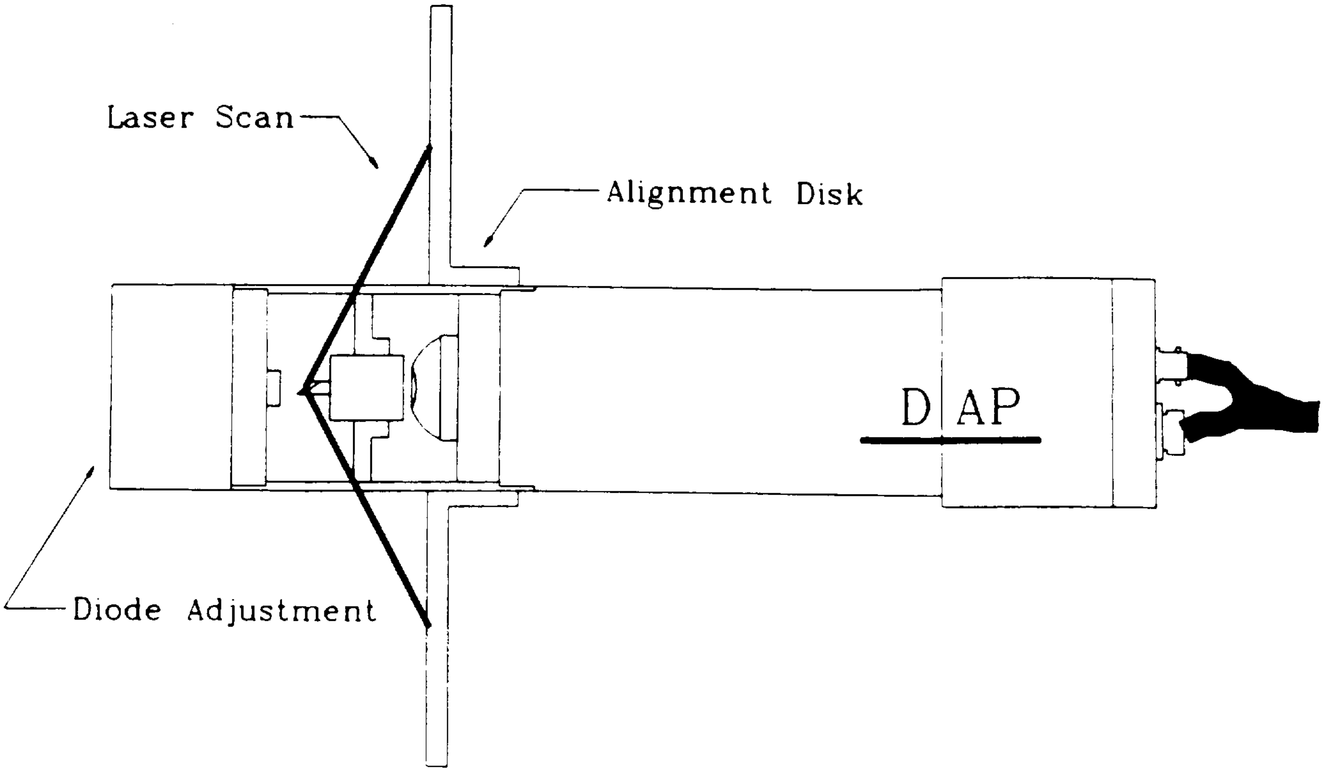


Figure 3.5 Alignment of the DAP for Measurement.

2. Remove the top cap of the probe by unscrewing it from the main casing.

3. Mount the probe in a stationary position allowing the concentric rings on the alignment disk to be clearly visible, while allowing easy access to the scanning system.

4. Insure that the alignment disk is sitting perpendicular to the window using a right triangle.

5. Turn the measurement power switch on the PVI on and adjust the laser intensity to high, as described in Chapter 2.

6. A complete and concentric ring should be projected on the alignment disk. If the ring is nonuniform or misaligned with those on the disk, the diode must be adjusted.

7. To obtain a uniform scan, adjust the tilt of the diode using the two large brass screws.

8. To obtain a scan which is concentric with the circles on the alignment disk, the diode must be translated. Translation in the plane of the diode, perpendicular to the projected beam, is achieved by adjusting the smaller of the brass screws. To translate in one direction, simultaneously adjust the two screws which diagonally oppose each other.

Chapter 4

CYLINDRICAL LIGHT RING (CLR)

When a measurement system and an encapsulated probe are not required, the Cylindrical Light Ring can be used allowing panoramic inspection to be performed simply. The assembly is comprised of the CLR, a 38 mm diameter PAL and its mount, 3 spacers, an f/1.4, 25 mm focal length transfer lens, and a Pulnix TM-7CN black and white camera.

Assembling The CLR For Panoramic Inspection

The CLR assembly is depicted in Figure 4.1. Note that the first spacer is different than that used with the DAP. Instructions for assembly are as follows:

1. Insert the PAL and its mount through the central hole in the CLR. Secure the CLR to the PAL mount using the four set screws located at 90° around the upper portion of the light ring.

2. Screw the PAL and its mount to the first spacer. Screw the remaining spacers and camera together as shown in Figure 4.1.

3. Attach the video and power connectors of the 4 pin composite cable to the base of the camera. Attach the red and black wires from the composite cable to the corresponding red and black wires of the CLR.

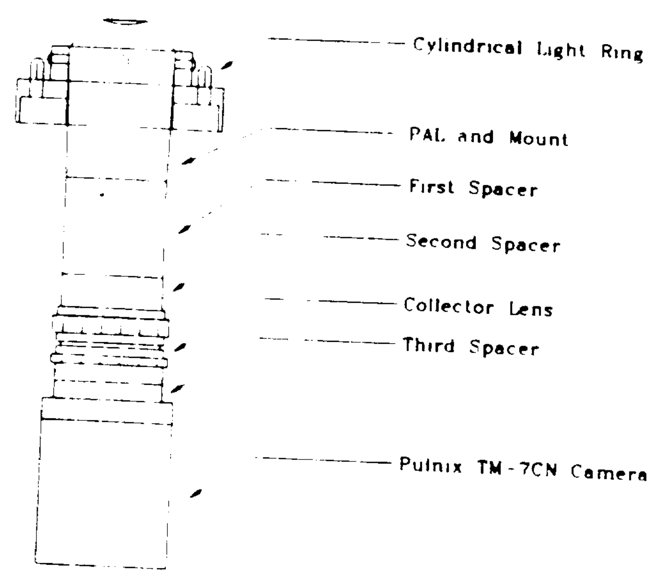


Figure 4.1 Cylindrical Light Ring (CLR) assembly.

4. Attach the opposite end of the composite cable to the PVI as described in Chapter 2. Turn the main power switch on and then turn on the illumination switch and the video.

5. Adjust the position of the CLR on the shaft of the PAL while viewing on the video

monitor.

Replacing The Light Bulbs In The CLR

The CLR uses (8) T-1 3/4, 12 volts, .075 amp miniature lamps.

Instructions for bulb replacement follows:

1. The broken/burnt bulb must first be removed by removing the soldered connection to the wiring and by loosening the set screw in the CLR.
2. Insert the new bulb into its position and insure that at least 3.18 mm (0.125") of an inch clearance exists between the end of the bulb and the wall of the light ring. Secure this position with the set screw.
3. Solder the end of the bulb to the wiring.

Chapter 5

USING THE CORTEX FRAME GRABBER

The CORTEX frame grabber is capable of grabbing a video image; displaying the video image directly from a video camera, or from memory; saving the video image to a file; restoring a video image from a file; loading a look-up-table; and grabbing a video image via an external trigger.

The steps required to acquire, save and retrieve data are outlined below. Additional details are included in the CORTEX-I operator's manual.

Getting Started

At the DOS prompt type in

C:\>cd cortex

The executable, v.exe, requires a drive letter to identify the video disk. To execute the program type in

C:**CORTEX**>v d:

The following menu will appear on the screen:

```
 Operating Mode                                          Display Source
Full   1buf   2buf   3buf   4buf                       Camera     Memory

        Quit        -    Quit program.
        Camera      -    Display live video from the camera.
        Memory      -    Display video from the memory.
        Grab        -    Grab and show memory image.
        Full/Quad   -    512x484 image (FULL/QUAD IMAGE).
        1buffer     -    256x242 image upper left quadrant.
        2buffer     -    256x242 image upper right quadrant.
        3buffer     -    256x242 image lower left quadrant.
        4buffer     -    256x242 image lower right quadrant.
        Trigger     -    Freeze video on trigger input.
        Load LUT    -    Load new look-up table.
        Save        -    Save video image to a file.
        Restore     -    Restore video image from a file.
        VGAview     -    View video  memory on PC VGA display.
```

To select a command, use the mouse or type the first or highlighted letter of the command line.

Acquiring an Image

To display a video image onto the monitor, use the Camera command by typing

c

Before freezing the image, the operating mode must be decided. To freeze the full image with high resolution, use the Full/Quad command by typing

f

Typing 1, 2, 3, or 4 allows only a quadrant of the image to be acquired.

To freeze or grab the image, use the Grab command by typing

g

The monitor no longer displays a live video image. To unfreeze the image type c. The "grabbed" image may now be saved.

Saving an Image File

To save the image, use the Save command by typing

s

A prompt line will appear containing the TIFFOUT command, the video disk letter (D:), image file name (IMAGE, 1BUF, 2BUF, 3BUF, or 4BUF), and the destination filename. For instance, if the operating mode is FULL, the following prompt will appear:

tiffout D:\image image

To change the destination filename from image to temp, use the backspace, insert, delete, and arrow keys to move the cursor. The line would appear as follows:

tiffout D:\image temp

The entire image is automatically stored in the CORTEX directory with the .tif extension as temp.tif. To cancel the Save command, press escape.

Retrieving an Image File

To retrieve a file from the CORTEX directory, the operating mode must be the same as the mode used for saving the file. Retrieve the file by using the Restore command and typing

r

A prompt line will appear containing the TIFFIN command, the default operating mode name (IMAGE, 1BUF, 2BUF, 3BUF, or, 4BUF), the correct video disk letter (D:), and the respective mode buffer area (IMAGE, 1BUF, 2BUF, 3BUF, or 4BUF). For instance, if the operating mode is FULL, the following prompt will appear.

tiffin image.tif D:\image

To change the source filename from the default operating mode name to temp, use the backspace, insert, delete, and arrow keys to move the cursor. The resulting line would appear as follows:

tiffin temp**.tif D:\image**

To cancel the Restore command, press escape.

Exiting the Program

To exit the program, type in

q

Chapter 6

USING PAL^{view} FOR IMAGE LINEARIZATION

PAL^{view} is a mouse driven, "user-friendly" program designed to study the annular image obtained from a *Panoramic Annular Lens* (PAL). This chapter is confined to image linearization; however, the *Digital Acquisition Probe* (DAP) may be used in conjunction with the PAL^{view} software to contour and measure dimensional changes in the structure surrounding the probe. This capability is discussed in Chapter 7.

Message boxes appear throughout PAL^{view} to provide instruction to the user. The interface is designed with an emphasis on simplification of use without high graphic overhead. The software currently runs on 386/486 IBM-PC AT compatible machines with standard VGA graphics requiring at least a 20 mgabyte hard drive and a Microsoft compatible mouse. For image capturing, the program uses either a Matrox, Imaging Technology or Cortex frame grabber to produce an image in TIFF format with a 38 mm diameter PAL attached to either a vidicon, CCD or CID video camera.

The program requires input and output files in TIFF format (<filename>.tif) as well as four (x,y) locations. The four locations determine the center and the inner and outer radii of the annular PAL image. In addition, the quadrant to be linearized must be specified. The origin of the coordinates is in the upper left corner of the image. 'x' values increase left to right, and 'y' values increase top to bottom. Both are numbered starting from zero.

Getting Started

At the DOS prompt type in

C:\>cd palview

To execute the program type in

C:\PALVIEW>pal

The image menu screen will appear on the screen. **Input File Name:** and **Output File Name:** lines appear on the left portion of the display, four buttons, **ABOUT**, **DELETE...**, **OKAY**, and **EXIT** appear at the bottom of the display, a **FILES** box is found on the right side of the display, and a button, **SQUARE**, for using images containing square pixels is located below **Input File Name:**.

Exiting the Program

Should it become necessary to exit the program, click on the

Exit

button located in the lower right corner of the screen.

About PAL[view]

For information concerning the capabilities of the program, use the mouse to move the cursor to the

ABOUT

button and click the left button on the mouse. A window will appear describing the program. To exit this window, click the mouse on the

OKAY

button located in the window.

Entering Files for Linearization

To linearize an image, the desired image file must be entered into the slot labeled

Input File Name:

Click the mouse in the slot. A "_" cursor will appear in the slot. The image file may either be entered by using the keyboard to type in the name or by using the mouse in the **FILES** box.

To use the **FILES** box, move the mouse cursor to the **FILES** box and locate the appropriate directory containing the image file to be linearized.

Technical Note: Sample images are contained in c:\palview\images.

To find a files outside of the palview directory, click on

\..

located in the box.

A list of directories in C: drive will appear. Move the mouse to the desired directory and click the left button. If the directory is not shown, use the slide bar to move up and down the menu.

Once in the desired directory, click the mouse on the image file to be linearized (.tif format). This will cause the image file to appear in the **Input File Name:** slot.

Most frame grabbers (CORTEX-I) produce TIFF images in non-square pixels and PAL[view] defaults to this option. Some frame grabbers (Imaging Technology, Matrox) may produce square pixels. If the input image has square pixels click the mouse on the

SQUARE

button.

To name the linearized output image, click the mouse in the

Output File Name:

slot. A "_" cursor will appear in the slot. The desired name may be typed in using the keyboard or an unwanted file from the **FILES** box may be overwritten by clicking the name into the **Output File Name:** slot.

To edit the input or output filename, click the mouse in the appropriate slot. Use the backspace, delete, and arrow keys to edit. The carriage return on the keyboard may also be used to move from the input to output filename slots and vice versa.

Linearizing an Image

To linearize the image file named in the **Input File Name:** slot, click the mouse on the

OKAY

button. The image and a cursor will appear on your display. The position of the cursor is displayed in the upper right corner of the screen. A message box in the lower center portion of the screen indicates to

Please select 4 points and a Quadrant
Click Okay when done.

Should it become necessary to return to the image menu screen, click the mouse on the

CANCEL

button.

In order for the program to calculate the center, and outer and inner radii of the annular PAL image, four points must be entered. The first three points must be entered on the outer radius of the image, preferably 120° apart. The fourth point must be entered on the inner radius.

Click the mouse on the

Point 1

button located at the upper left corner of your screen. A message box appears asking to

select point 1 on the outer radius.

Move the cursor to the outer radius of the image and click the left button on the mouse. The coordinates of this point will appear in the **Point 1** box.

Click the mouse on the

Point 2

button located at the upper left corner of the screen. A message box appears asking to

select point 2 on the outer radius.

Move the cursor to the outer radius of the image and click the left button on the mouse. The coordinates of this point will appear in the **Point 2** box.

Click the mouse on the

Point 3

button located at the upper left corner of the screen. A message box appears asking to

select point 3 on the outer radius.

Move the cursor to the outer radius of the image and click the left button on the mouse. The coordinates of this point will appear in the **Point 3** box.

For best results, select the three points approximately 120° apart.

Next, click the mouse on the

Point 4

button located at the upper left corner of the screen. A message box appears asking to

select point 4 on the inner radius.

Move the cursor to the inner radius of the image and click the left button on the mouse. The coordinates of this point will appear in the **Point 4** box.

Technical Note: PAL^{view} stores the last configuration used for image linearization in memory. Before entering the 4 points, the image may be examined for the 4 crosses which denote the previously stored locations. If these points are already located on the outer and inner radii of the current image, it is not necessary to enter 4 new points.

After selecting the 4 points, choose a quadrant of the image to be linearized.

Following is a list of the choice of quadrants and their meanings:

N North
S South
E East
W West
1 First Quadrant (Upper right corner)
2 Second Quadrant (Upper left corner)
3 Third Quadrant (Lower left corner)
4 Fourth Quadrant (Lower right corner)

Click the mouse on the desired direction (**N**, **S**, **E**, **W**, **1**, **2**, **3**, or **4**) located in the lower left corner of your screen.

To begin the linearization process, click the mouse on the

LINEARIZE

button.

Technical Note: An error message will appear if the data required for linearization is incomplete. Acknowledge the error by clicking the mouse on the ! button and provide the required information.

If 4 new points are entered, as opposed to keeping the existing points, a message box will appear.

Configuration points have changed!
Do you wish to save new points?

Clicking on **Yes** will store the new configuration. Click on

Yes or **No**

An hourglass will appear indicating that linearization is in progress; the status is displayed directly below the cursor coordinates. The linearized image will then appear on the screen. A message box will appear saying

Linearization complete
Click Okay to linearize another image
Click Exit to terminate the program.

To linearize another image, click on the

Okay

button located in the lower right corner of the screen. The program will return to the image menu screen.

Deleting a File

A file may be deleted from the image menu screen. Click the filename of the file to be deleted into the slot labeled

Input File Name:

Click the mouse on the

DELETE

button.

Chapter 7

USING PAL^{view} FOR OPTICAL MEASUREMENT

The *Digital Acquisition Probe* (DAP) may be used in conjunction with the PAL^{view} software to contour and measure dimensional changes in the structure surrounding the probe.

Calibrating The DAP

Calibration of the DAP has been performed to relate the radial offset distance (the perpendicular distance from the optical axis of the DAP to the surface under study) to the position of the point in the annular image. During this calibration, the DAP scan was projected on a surface that was progressively moved away from the optical axis of the imaging system. At incremental radial offset values, an image was acquired and the position of the scan measured relative to the center of the annular image was determined. The data was then subdivided into three regions and curve fitted. These functions have been incorporated into the PALview program and are shown in Figures 7.1-7.3. The corresponding functions were incorporated into the PAL^{view} program. The four point configuration used during calibration was (269,51), (95,355), (445,355) and (269,153). For the points considered, the image is centered at (270.00,253.37) and has an inner radius equal to 100 pixels and an outer radius equal to 202 pixels. The scan angle of the mirror is 32.2° measured with respect to the optical axis of the DAP.

The sensitivity (inches/pixel) of the DAP versus the radial offset distance (inches) for the three regions is plotted in Figures 7.4-7.6. It is obvious from these graphs that the DAP is most accurate when measuring dimensional changes in structures with relatively small inner diameters, ie., approximately 3.6" to 8".

Making The Measurement

Use the DAP to obtain an image including a laser scan.

Technical Note: The image test.tif, contained in c:\palview\images, is a sample of a test pattern wrapped around the inner wall of a 12.7 cm (5") diameter pipe. An inclusion is positioned in the bottom of the pipe. The diameter of the pipe may be verified by measuring the offset for two diametrically opposed points on the scan.

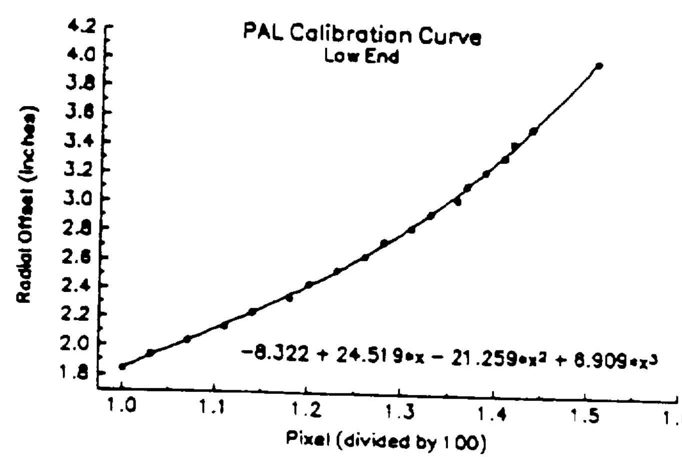


Figure 7.1 Calibration curve for points relatively close to the PAL (low end).

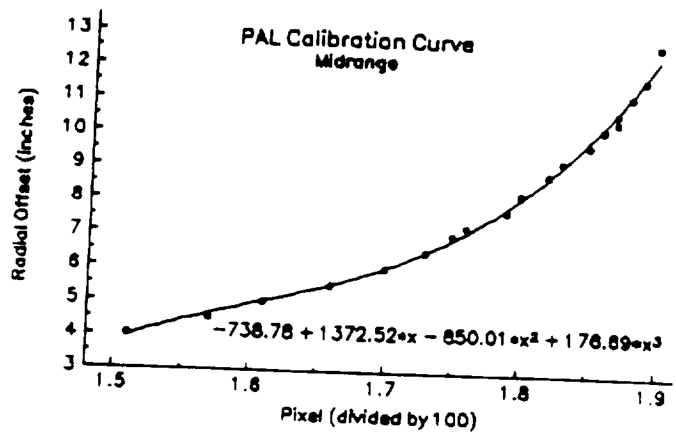


Figure 7.2 Calibration curve for points in the midrange.

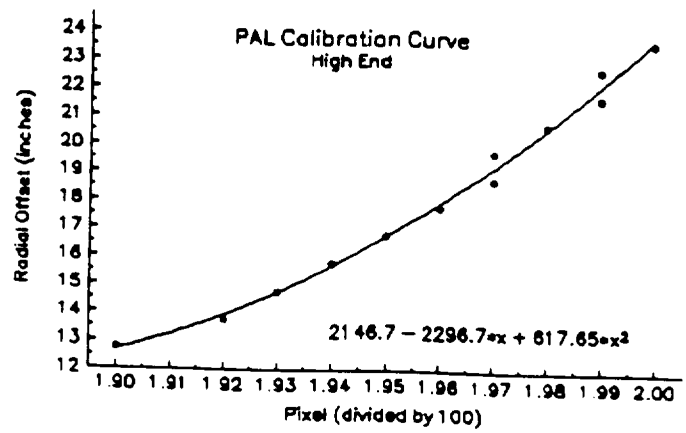


Figure 7.3 Calibration for points relatively far away from the PAL (high end).

Following the procedure outlined in Chapter 6, display the image using PAL[view] and select the four configuration points and any one of the eight quadrants. Click the mouse on the

Measure

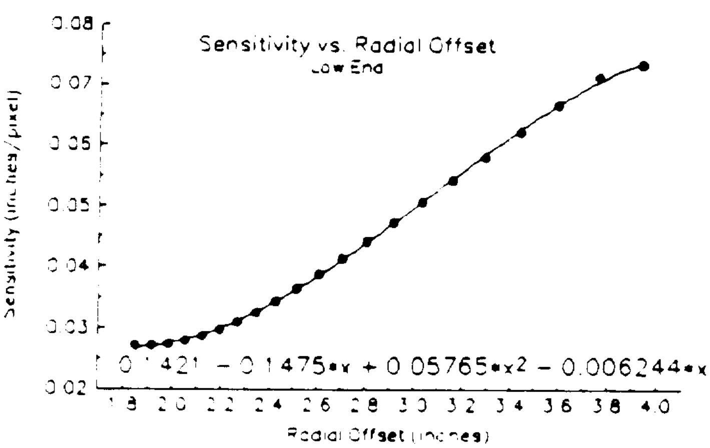


Figure 7.4 Sensitivity curve for points relatively close to the PAL (low end).

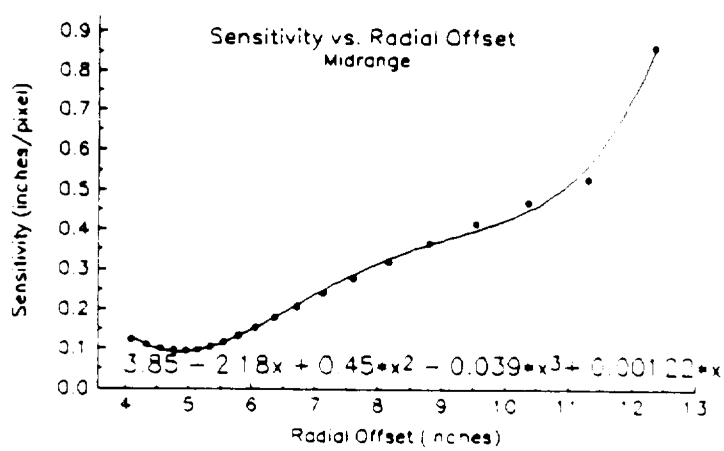


Figure 7.5 Sensitivity curve for points in the midrange.

button located in the lower right corner of the screen. A message will appear to

select reference point of measurement

Position the cursor at a point on the image with the cursor located midway between the leading and trailing edge of the scan. Click the left button of the mouse. The polar coordinates of the point [r (radius) in pixels; θ (angle) in degrees] measured relative to the center of the annular image are displayed along with the radial offset (in inches) in the upper right hand corner of the screen.

Technical Note: An error will appear if a point is chosen outside of the annulus. Acknowledge the error by clicking the mouse on the ! button and provide the required information.

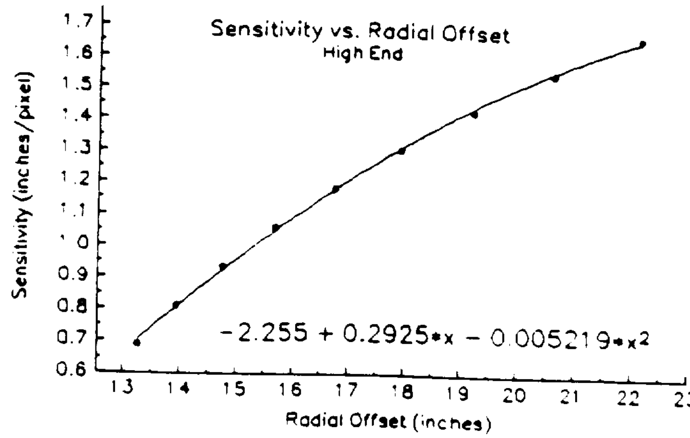


Figure 7.6 Sensitivity curve for points relatively far away from the PAL (high end).

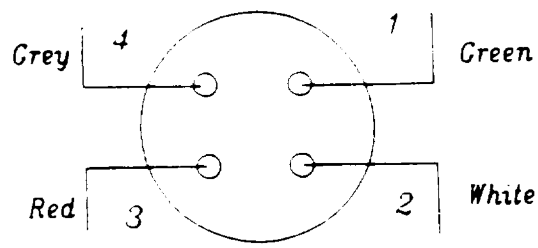
Other points can be selected. After the desired measurements have been taken, click the mouse on either the

Cancel or **Linearize**

button and proceed according to the procedure outlined in Chapter 6.

Appendix

THE PANORAMIC VIDEO INTERFACE (PVI)



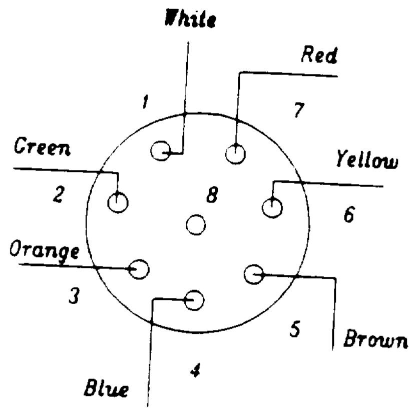
1 Video (+)

2 Video (-)

3 Illumination

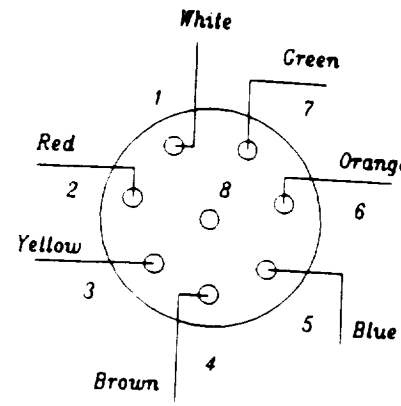
4 Illumination (ground)

Figure A-1. 4-Pin Connector And Cable For The CLR.



Interface side

1 Video (+)
2 Video (-)
3 Illumination
4 Illumination (ground)
5 Laser and Motor (-)
6 Laser (control)
7 Laser (+)
8 Motor (+)



Probe side

1 Video (+)
2 Laser (+)
3 Laser (control)
4 Laser and Motor (-)
5 Illumination (ground)
6 Illumination
7 Video (-)
8 Motor (+)

Figure A-2. 8-Pin Connector And Cable For The DAP.

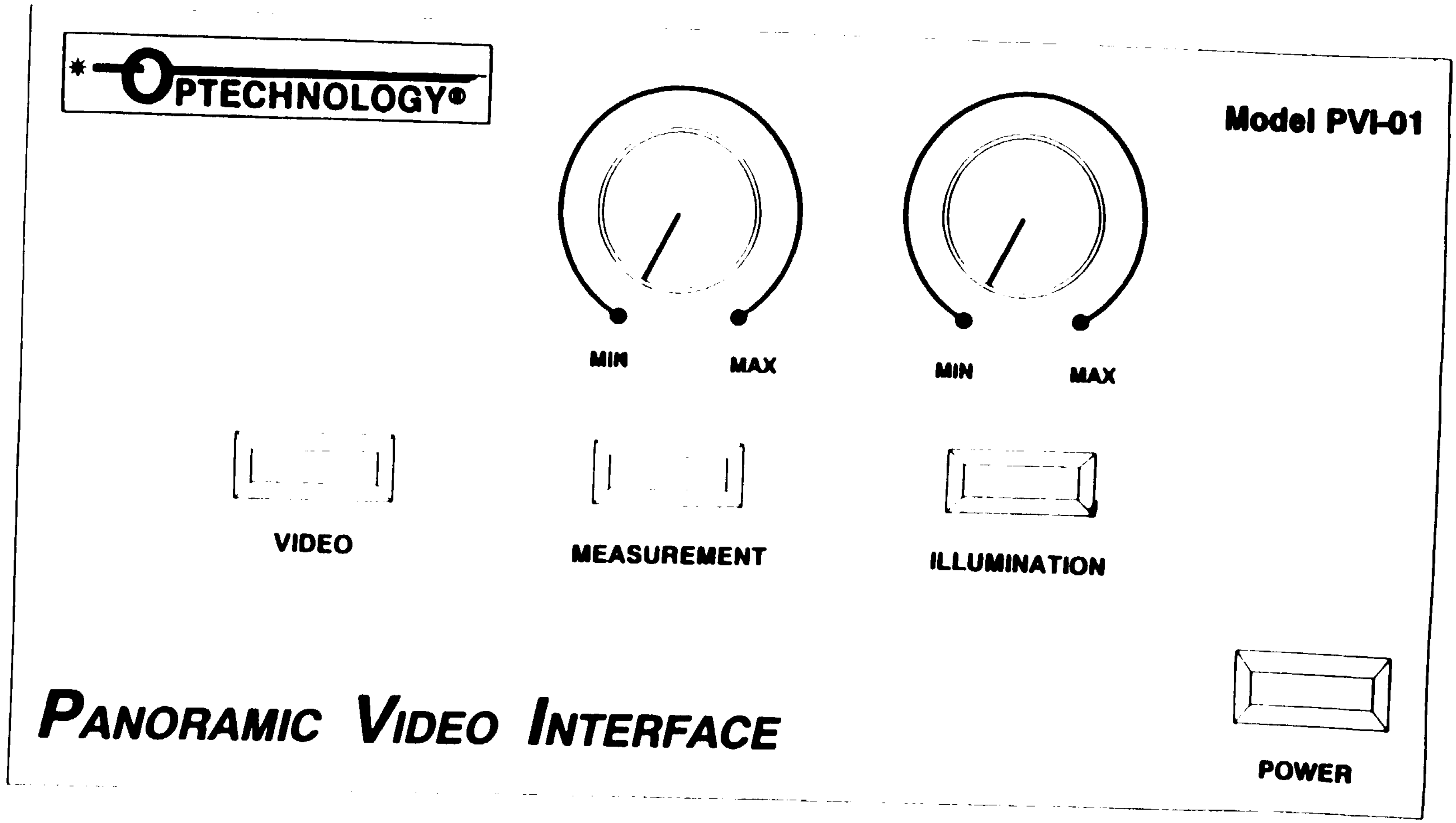


Figure A-3. Front Panel Of The PVI-01 Power Supply.

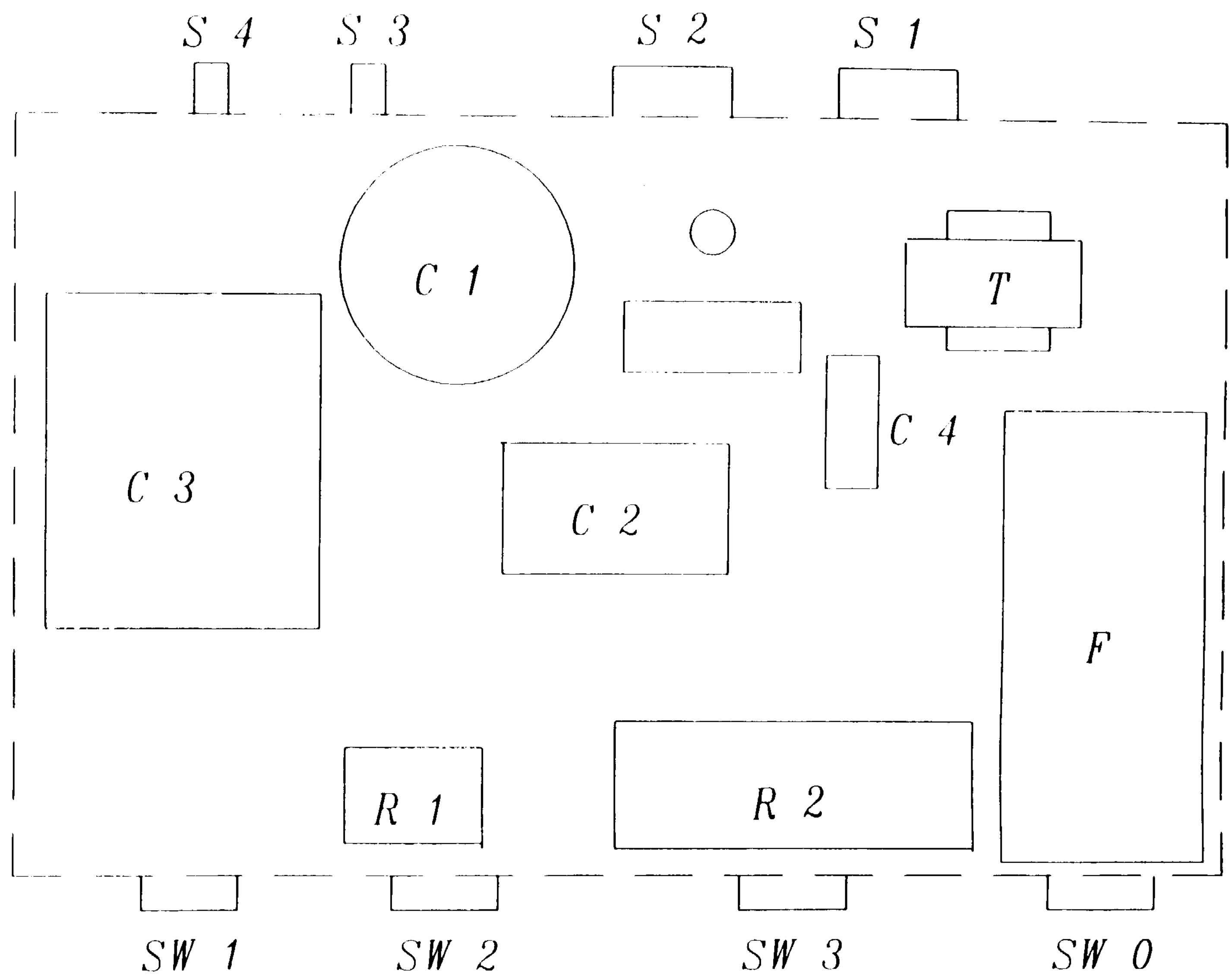


Figure A-4. Interior Layout Of The PVI-01 Power Supply.

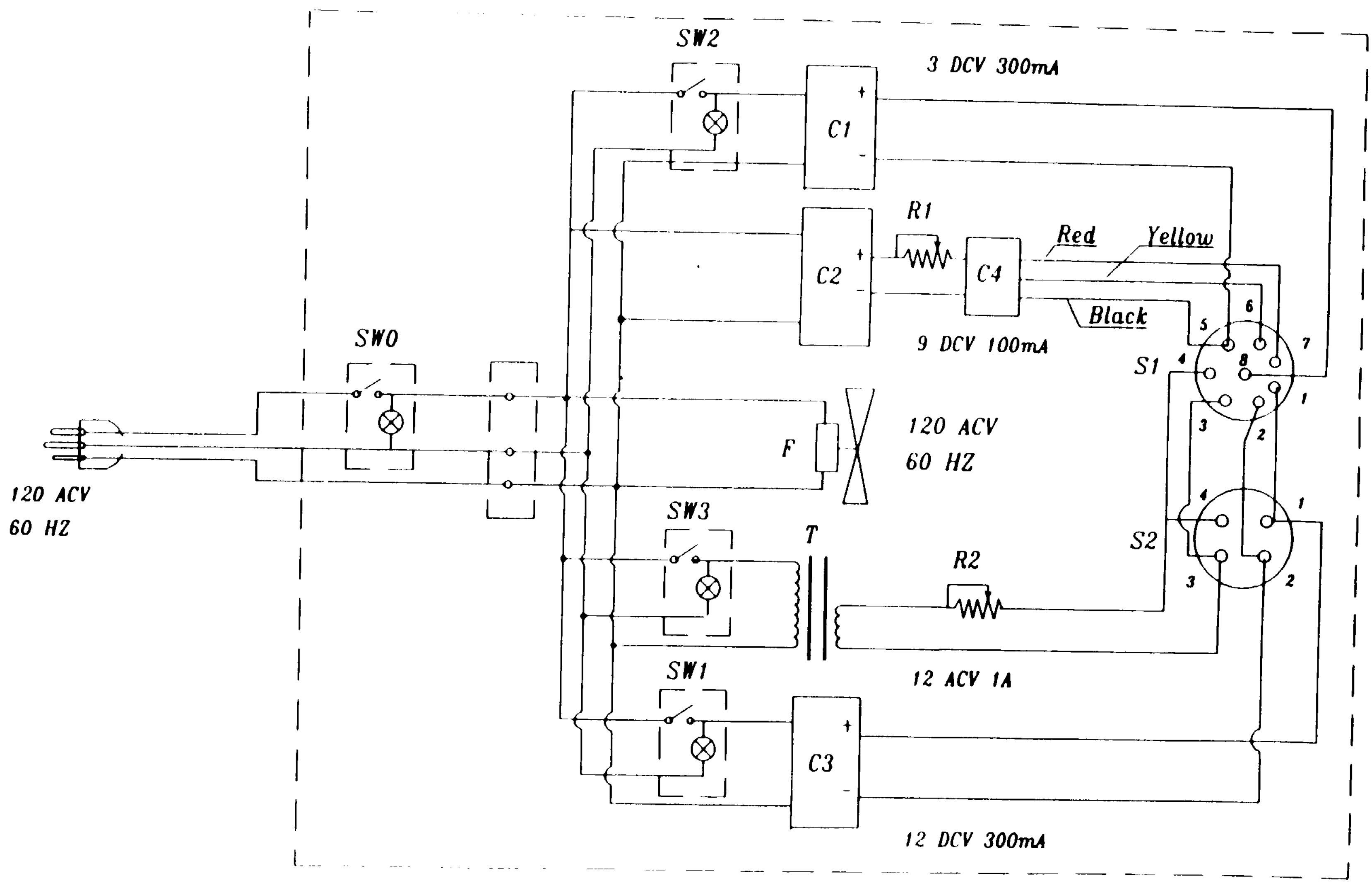


Figure A-5. Circuit Diagram For The PVI-01 Power Supply.